ARTICLE

Survey on Scientific Shared Resource Rigor and Reproducibility

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Shared scientific resources, also known as core facilities, support a significant portion of the research conducted at biomolecular research institutions. The Association of Biomolecular Resource Facilities (ABRF) established the Committee on Core Rigor and Reproducibility (CCoRRe) to further its mission of integrating advanced technologies, education, and communication in the operations of shared scientific resources in support of reproducible research. In order to first assess the needs of the scientific shared resource community, the CCoRRe solicited feedback from ABRF members *via* a survey. The purpose of the survey was to gain information on how U.S. National Institutes of Health (NIH) initiatives on advancing scientific rigor and reproducibility influenced current services and new technology development. In addition, the survey aimed to identify the challenges and opportunities related to implementation of new reporting requirements and to identify new practices and resources needed to ensure rigorous research. The results revealed a surprising unfamiliarity with the NIH guidelines. Many of the perceived challenges to the effective implementation of best practices (*i.e.*, those designed to ensure rigor and reproducibility) were similarly noted as a challenge to effective provision of support services in a core setting. Further, most cores routinely use best practices and offer services that support rigor and reproducibility. These services include access to well-maintained instrumentation and training on experimental design and data analysis as well as data management. Feedback from this survey will enable the ABRF to build better educational resources and share critical best-practice guidelines. These resources will become important tools to the core community and the researchers they serve to impact rigor and transparency across the range of science and technology.

Key Words: core, reproducibility, rigor, shared resource, transparency

INTRODUCTION

Biomedical research is a process of exploring the unknown, deconstructing the complexity of life processes and the pathology of disease, and applying new discoveries to improve and advance the lives of humans, animals, and society. As scientists, we build on existing knowledge, taking incremental steps toward understanding with the occasional leap forward provided by a major discovery or paradigm shift. Science advances through the publication of novel results and independent replication studies upon which others in the field build new hypotheses to better elucidate biologic processes. Reproducible research practices include rigorously controlled and documented experiments using validated reagents. These practices are integral to the scientific method, and they enable acquisition of reliable and actionable research results. However, the art and practice of science is affected by challenges that go beyond the inherent complexity of the biology being explored. The pressures to publish, the focus on novel, positive, and impactful results, the use of suboptimal research practices, and the scarcity of research funding likely contribute to unacceptable levels of irreproducible scientific results.[1, 2]

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A recent survey conducted by *Nature* (2016) reported that 90% of participants identified "more robust experimental design" as one of several key improvements needed for the conduct of better science, in addition to "better statistics" and "better mentorship."[3] More recently, *Nature Human Behavior* published a manifesto for reproducible science.[4] The researchers discussed why measures to optimize elements central to the scientific process such as methods, reporting and dissemination, reproducibility, evaluation, and incentives are essential to improve the transparency, reproducibility, and efficiency of scientific research. The researchers made several recommendations and called attention to initiatives like the Transparency and Openness Promotion guidelines created by the Center for Open Science to improve research planning and reporting.[5] Currently, over 5000 journals and research organizations have signed on as journal or organization signatories to demonstrate their support for and planned commitment to the principles of the Transparency and Openness Promotion guidelines.[4, 5]

The scientific research community continues to focus on issues surrounding scientific rigor and transparency, with proposals to improve research practice initiated by funding agencies, scientific journals, researchers, and research institutions. On June 9, 2015, the U.S. National Institutes of Health (NIH) published a notice (NOT-OD-15-103) that identified 4 areas for improvement that are now required to be addressed by scientists in grant applications. These 4 areas are as follows: 1) scientific premise forming the basis of the proposed research, 2) rigorous experimental design for robust and unbiased results, 3) consideration of sex and other relevant biologic variables, and 4) authentication of key biologic and chemical resources.

Through these 4 elements, the NIH intends to "enhance the reproducibility of research findings through increased scientific rigor and transparency." Although the lack of rigor and transparency is usually not caused by purposeful bad behavior, the worst-case scenario may reflect or be misconstrued to reflect research misconduct. According to the Office of Research Integrity data on findings of research misconduct over the period 2006–2015 (*https://ori.hhs.gov/images/ddblock/ORI%20Data%20Graphs%202006-2015.pdf*), respondents in such cases skew heavily toward relatively unexperienced or untrained researchers. In that time frame, 90 of 125 cases with findings of misconduct involved students, technicians, post-docs, and junior faculty. The overwhelming majority of these cases involved falsification or fabrication of data. It is noteworthy that this cohort tends to be the major user group of any shared resource; they are the "boots on the ground" for lab-based science and are most likely to interact with core facilities and core personnel. Therefore, research cores have a critical role in defining rigorous methods for acquiring and analyzing data. The process for effectively transmitting these methods and concepts to users of a core is through modeling and training. In addition, core scientists have a lasting impact on the responsible conduct of research by mentoring researchers at all levels in the necessary skills associated with experimental planning and design, appropriate data analysis techniques, and accurate presentation and reporting of results.

Within this broader global conversation about research quality, it is important to emphasize the critical role that shared research resources can play in achieving efficient use of research funds and broadening access to advanced skills, expertise, and technologies. Shared scientific research resources generate the majority of research data at many institutions, so their role in maintaining needed expertise and generating quality data is considerable.[6] Recognizing this, federal granting agencies have already made significant investments in shared resource cores *via* a variety of direct and indirect mechanisms with the goal of providing cutting-edge technologies and expert consultation to individual scientific investigators.[6] Therefore, the scientific shared resource community must continue to take the lead in promoting and supporting rigorous, transparent, and reproducible research (R&R), as well as in providing critical mentoring and technical training.

The Association of Biomolecular Resource Facilities (ABRF) is an international scientific society of scholars whose mission is to advance technologies, education, communication, and reliable research in shared scientific resource facilities. The ABRF Committee on Core Rigor and Reproducibility (CCoRRe) was formed to provide guidance to shared resource leaders and their staff members as they strive to operate in a rigorous, reproducible, and transparent manner. The CCoRRe recently conducted a survey to assess how shared resource facilities are currently assisting investigators with their need to demonstrate transparency and rigor in their research. In addition, the survey captured information from the shared resource personnel related to the challenges they face and the resources they need to support scientific transparency, rigor, and reproducibility.

MATERIALS AND METHODS

Survey Overview

The CCoRRe committee developed an 18-question online survey and shared it using SurveyMonkey (*https://surveymonkey.com/r/CCoRRe_2017*). The survey was announced on the ABRF listservs and blogs and was open from February to April 2017. All survey participants remained anonymous.

Data Analysis

The survey contained both multiple-choice and open-ended text questions. Results from the multiple-choice questions were calculated by counting the number of responses for each element for a given question. The open-ended text questions were evaluated by first conducting an inductive content analysis of text to categorize the responses. At least 2 committee members then independently coded text units using these categories. After the independent coding, the committee members discussed any discrepancies and reviewed differences to determine if consensus could be reached. Results reflect the mean counts of responses in each category.

RESULTS AND DISCUSSION

Survey Demographics

A total of 243 individuals from 21 countries completed this section, and 53% identified themselves as members of the ABRF. The majority of the survey participants are core facility directors or managers (69%) and work in an academic setting (72%) in the United States (79%). A wide range of technologies was represented by the participants as seen in Fig. 1, enabling sampling of a large cross section of core technologies.

Current Landscape for Rigor and Transparency in Represented Shared Resources

When asked how knowledgeable participants were with respect to the NIH research rigor initiatives, 47% stated they were very familiar, whereas the rest were equally either somewhat familiar or completely unaware of such guidelines (Fig. 2).

Using an open-text format question, respondents were asked to describe why rigor and reproducibility is a challenge in scientific research. The 213 individuals (88%) that responded to this question provided a total of over 400 factors contributing to the ability to perform rigorous and reproducible research. The factors were grouped into the 9 separate categories listed in Table 1. The lack of training, mentorship, expertise, or oversight was the predominant factor identified as contributing to the lack of rigorous research procedures. In the following example, a respondent wrote that there is not enough training for individuals doing the research: “Lack of proper training, full understanding of technology, proper controls. I think every graduate student should have to take a ‘how to do research’ course.” “We spend a lot of time teaching our users how to ‘do science’ before we even get to training them how to do flow (flow cytometry).” Another respondent implied that research laboratories are not providing adequate mentoring to new personnel, writing the following: “Chiefly a lack of trained senior personnel in research labs, post-docs, and senior graduate students, who simply are not available to mentor younger students and train them properly in the use of controls. The PI’s don’t always have the time to keep on top of the work of junior personnel and probably assume that experiments were carried out in a well-controlled manner.”

Time pressures associated with publishing and grant preparation were frequently identified as risks to research rigor. One respondent noted that the scientific community needs to reevaluate how success should be evaluated, saying the following: “The measure of success in the scientific community is incorrect. There is too much emphasis on the number of papers a researcher publishes and not enough on the quality of the papers. As a result, fly-by-night journals

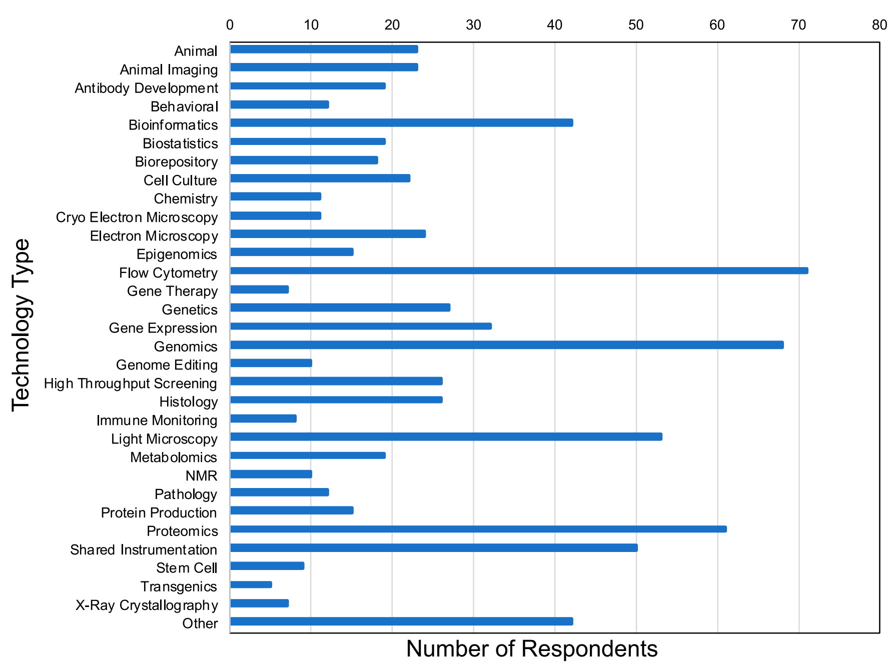

FIGURE 1

Technologies supported by the survey respondents. Respondents were able to select more than 1 technology type. NMR, nuclear magnetic resonance.

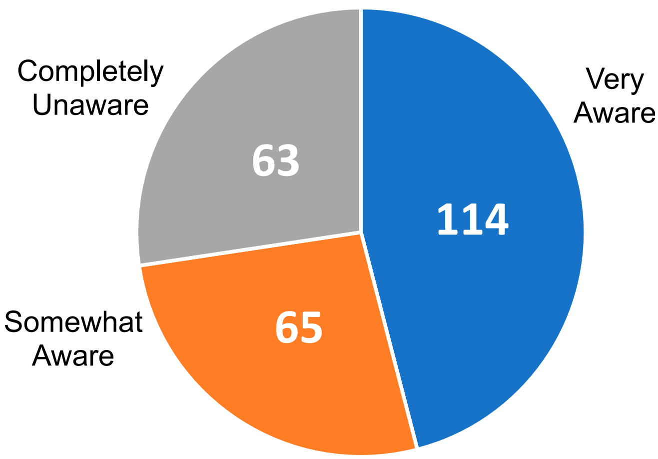

FIGURE 2

Survey respondents' self-assessments of their knowledge and awareness of the current NIH guidelines on rigor and reproducibility.

pop up and report less-than-trustworthy data that cannot often be reproduced. We should be policing ourselves much better than we are."

Many respondents noted that inadequate standardization of protocols and procedures across the research life cycle, from study planning through data analysis and reporting, contributes to variable research quality. As previously reported,[1, 7, 8] respondents indicated that experimental design deficiencies (involving sample size, quality control, and replication) and cost considerations could generate risks to research rigor and transparency.

Elements outside of the core environment that can influence research rigor include inadequate peer review. By providing insufficient information within their submissions, research scientists might limit the potential for an effective review. On a related front, reviewers may lack the necessary expertise to evaluate sections of a manuscript, leading them to overlook weakness in reported results.

These observations are similar to those previously reported from a *Nature* survey of 1576 researchers who responded to an e-mailed or online questionnaire on research reproducibility.[9] More than half of respondents indicated that pressure to publish and selective reporting negatively influence research rigor. Most scientists (about 90%) believed that experimental design, statistical approaches, and mentoring all needed to be improved.[9] In addition, previous reports have identified the lack of standards in basic biologic research as a key risk for research quality. The standardization of techniques, analyses, and reporting are critical for new, complex, and specialized technologies, which makes this limitation highly relevant for core service centers.[6]

Table 2 represents the responses from core personnel on the perceived challenges they face in promoting best practices for rigorous research in their core settings. Many of the categories listed in Table 1 regarding overall R&R compliance challenges reflect concerns challenging cores. Issues associated with sample quality or quantity top the list. One respondent noted the following: "I don't prepare the samples; people bring me samples to work with. I have no control over how the samples are prepared or what controls are prepared, which means generating reproducible results really falls on the investigator who I'm working with." The respondents reported significant challenges in their ability to generate reproducible results that are directly linked to the quality of the samples provided (contributing to preanalytical error) and the lack of stringency in experimental design (insufficient replication and controls) within projects submitted by investigators.

The comment "…researchers who want to 'go ahead anyway' despite all our concerns about poor samples" represents a challenge factor noted by a number of respondents. This raises the question of whether cores can or should report clear quality disclaimers or refuse to process samples that do not meet quality requirements, because poor sample quality may result in poor quality data, leading to inaccurate or misleading results and inference. This is an important consideration for shared scientific resources. The most common causes of errors that occur throughout typical laboratory testing process activities (preanalytical, analytical, and postanalytical processes) occur in the preanalytical

TABLE 1

Factors contributing to lack of compliance with R&R guidelines

Category	Number of responses[a]
Lack of training, mentorship, technical expertise or oversight	79
Time pressures	67
Inadequate standardization of protocols, guidelines, and data analysis	54
Poor experimental design, including sufficient replicates, sample size, and adequate controls	45
Experimental cost	40
Inappropriate experimental and analytical tools	36
Irresponsible research conduct	31
Incomplete documentation of experiments and data management	27
Inadequate peer review	13
Responses that could not be assigned to a category[b]	32

[a]Average number of responses from 3 scorers.
[b]A category was not created unless five similar responses were obtained. Examples of unassigned responses include: "It's the Wild West, and we like it that way?, Is it really inadequate?, The increasing drive to commercialise research, and No rules."

TABLE 2

Major challenges to rigor observed in shared resources

Category	Number of responses[a]
Poor sample quality from users/sample variability/limited biological material	51
Lack of well-trained principle investigators and lab members/Poor oversight	45
Poor experimental design: Lack of sufficient replicates/inadequate sample size/lack of adequate controls	43
Inadequate standardization of protocols or guidelines, and data analysis	43
Cost and time	39
Failure to leverage the core's expertise/following the core's advice/no consulting beforehand	23
Inadequate documentation of experiments/data management	19
Instruments: maintenance, upgrades, changes	15
Responses that could not be assigned to a category[b]	11

[a]Average number of responses from 3 scorers.
[b]A category was not created unless five similar responses were obtained.

phase of laboratory activity, which is typically not under the direct control of shared resource laboratory personnel.[10]

Challenges arising from the want of resources (specifically time and funding) were noted, as were challenges associated with the relationship between investigators and core personnel. Respondents reported that investigators frequently fail to avail themselves of core expertise through early and comprehensive consultation with core personnel. One respondent commented "the greatest challenge is getting researchers to seek out our assistance from the beginning. Seeking out our guidance before they design their experiments and collect data will improve rigor and reproducibility."

Ultimately, all research is limited by available financial resources and time constraints. However, investigators who fail to acknowledge the collective wisdom of the facility staff are making a mistake by failing to ask for or follow such expert advice. This greatly enhances the potential for unreliable or questionable research outcomes.

The importance of equipment management was also identified within the survey. Research core service labs are uniformly dedicated to maintaining instrument operation at levels that meet or exceed installation performance specifications. This is achieved by establishing rigorous schedules for preventive maintenance and using well-controlled, validated methods and workflows. It is likely that the experimental rigor will be degraded when "state-of-the-art" instrumentation is not properly maintained or when cores are not provided the resources needed to validate new technologies prior to use in research.

Interestingly, although factors that impact research reliability can be easily identified by the core's professional staff, the vast majority of surveyed participants (~85%) are currently not engaged in any efforts to address rigor and reproducibility at their home institutions. This may be explained by the lack of formal institutional policies supporting rigor and reproducibility such as the NIH initiative (noted by 75% of respondents). This finding is exacerbated by the low priority placed on rigor and reproducibility concerns by core customers (Fig. 3). Just over 70% of respondents noted that their clients do not routinely request specific information (documentation or practice statements) related to the procedures used by the cores to foster rigorous and reproducible research (Fig. 3).

The apparent lack of core engagement at the institutional level does not necessarily reflect a general lack of rigor in the daily operations of the cores. Indeed, 213 out of 216 who participated in this section of the survey selected at least 1 tool that they currently use to support R&R in their daily core operations. Documentation, in the form of quality control and standard operation procedures (SOPs), was reported by at least 170 (~80%) respondents as a tool used to support R&R practices in their cores (Fig. 4). Interestingly, the incorporation of an instrumentation management plan, a key component of many cores, was not as highly utilized (56%) of a tool. Oversight of data analyses and double-checking results were some of the least widely used (26%) tools by cores. Over

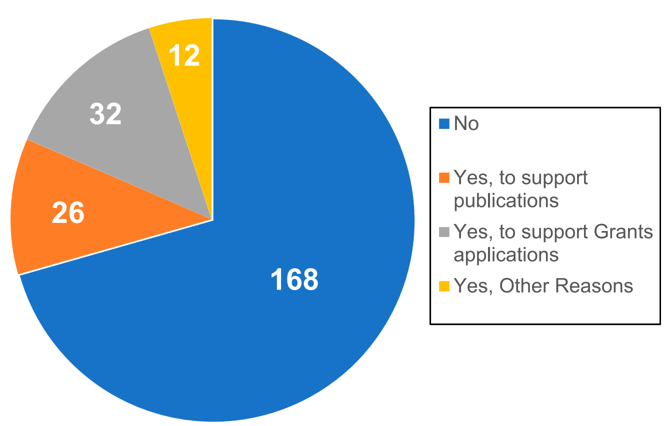

FIGURE 3

Lack of requests for rigor and reproducibility documentation by users of shared resources. Response to the following multiple-choice question: Has your core's rigor and reproducibility practice statement ever been requested?

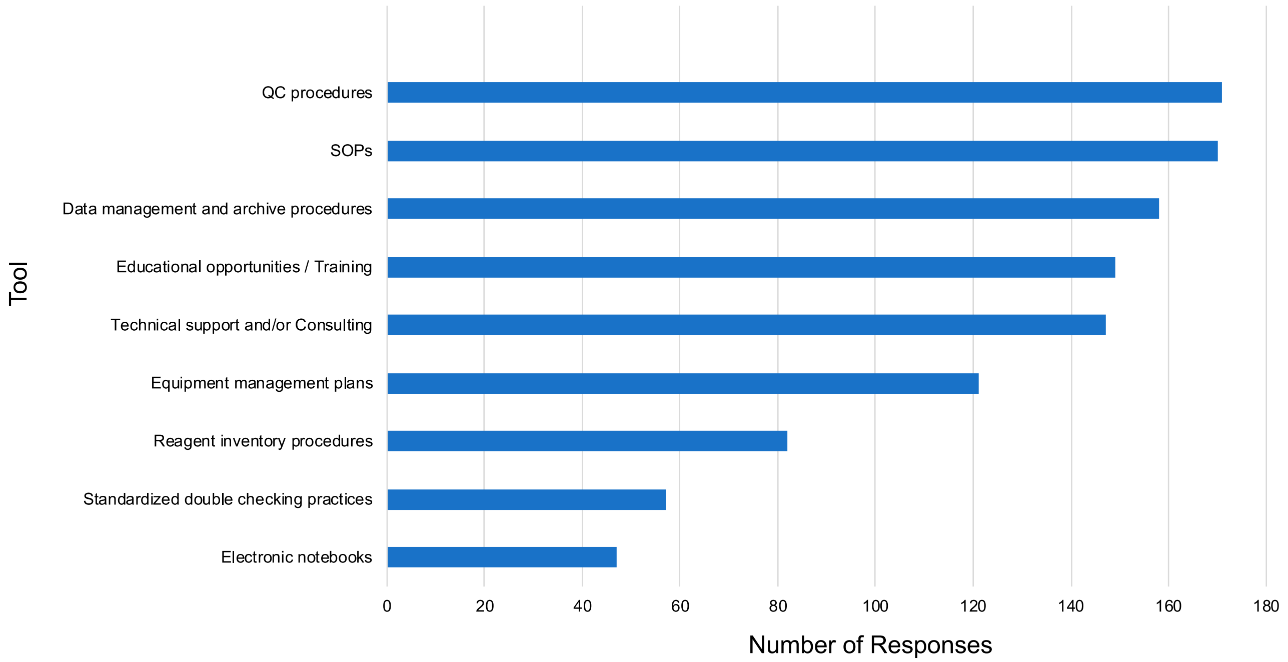

FIGURE 4

Usage of tools to promote rigor and reproducibility in research supported by core facilities. Number of respondents that indicated they use a given tool is shown. Respondents were able to select more than 1 tool. QC, quality control.

75% (224 respondents) incorporated at least 4 tools, and nearly half (105 respondents) have adopted 6 or more tools to ensure R&R in their operations. It appears that most cores are taking some steps to integrate and implement best practices to support research rigor and reproducibility. However, other important best practices (effective equipment management and quality checkpoints like double-checking) are not routinely implemented. When 1576 individual scientists responded to the 2016 *Nature* survey, 34% reported that they have not established procedures for reproducibility, 33% reported that they have established some procedures to foster research reproducibility within the past 5 years, and 33% report that they have had some procedures in place for more than 5 years.[9]

A second set of multiple-choice questions asked participants to select the new tools they think would enhance or facilitate the implementation of R&R best practices within their core operation. Of these options, "mandatory consultation between the core and investigator prior to rendering services" as well as "integration of standardized procedures for management of data, equipment, personnel, reagent, specimen, supplies, methods, and environment" were the most popular, followed by access to "stringent method validation and documentation" (Fig. 5).

Core Implementation of Research Best Practices

We surveyed the participants using open-ended questions to identify the major roadblocks that prevented the implementation of appropriate R&R initiatives in their specific cores in their home institutions. Three percent of the 216 participants reported no difficulties and 16% identified the "lack of uniform guidelines" as a major barrier. The lack of specified requirements or mandates from the funding agencies, journals, and institutions was considered to limit the ability of core laboratories to adopt universal guidelines, especially in light of the diverse technologies and research fields that core services are developed to serve. Many participants report that a change in the current research culture is needed to encourage staff and users to embrace rigor as a critical and supportive activity rather than see it as an obstacle to efficient and cost-effective core operation. Nearly 45% of cores reported "lack of buy-in" from their customers, which supports the previously mentioned survey responses reporting inadequate investigator training related to the factors that contribute to research reliability. Respondents note that the users, customers, and investigators will often resist the steps a core must take to implement and maintain rigor in their daily core operations. Without support from the institution, cores reportedly lack the authority to apply their expertise to positively influence the outcome of the research presented to them. In these situations, core staff may feel undervalued as contributing research partners and unable to mitigate the impact of poor processes or procedures. In addition, 13% of respondents report that the implementation of R&R can be difficult within the cores themselves because of resistance or

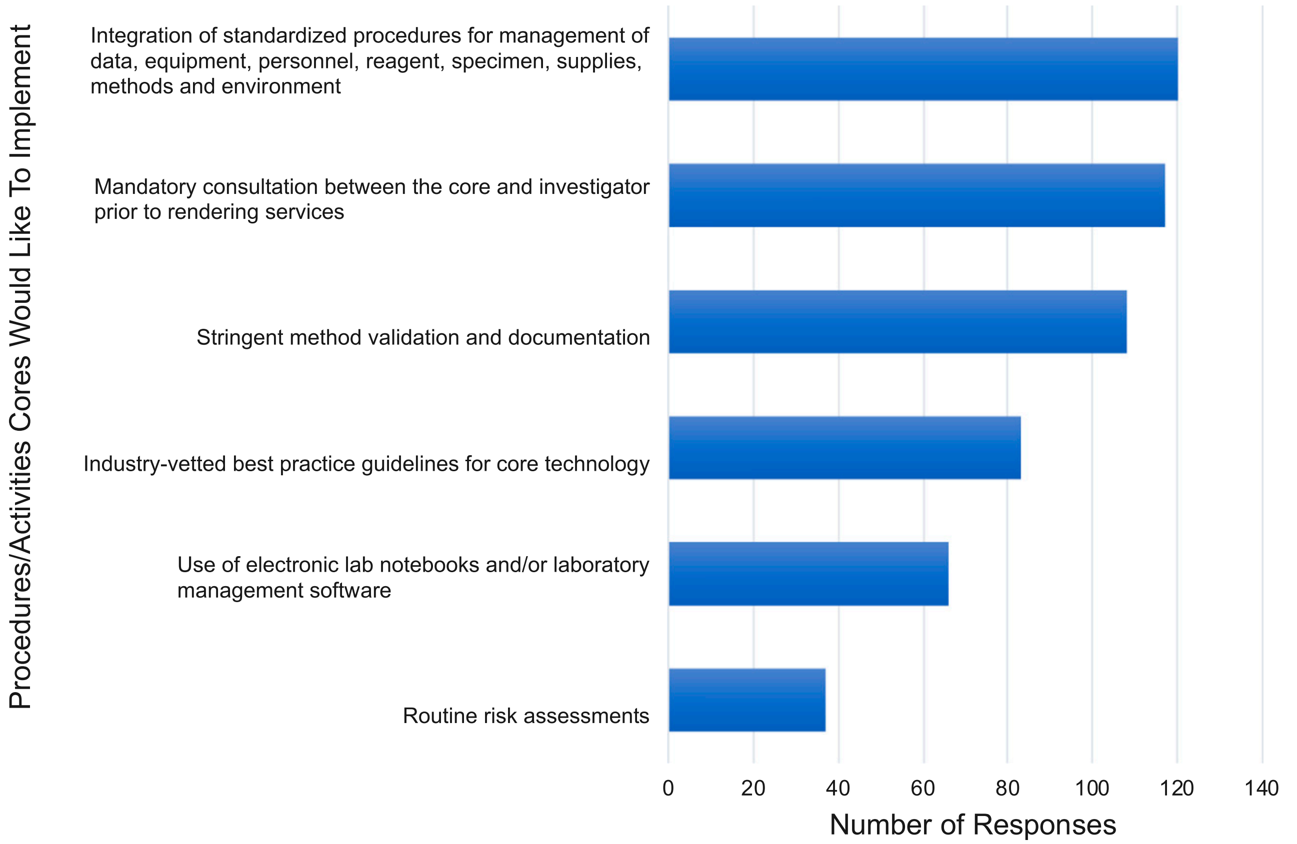

FIGURE 5

Types of tools that cores would like to implement in their operations. Respondents were able to select more than 1 tool.

lack of buy-in by professional staff and a systemic lack of core accountability or leadership.

Optimal research core services require a full commitment to rigorous methods as an obligation and not as a choice. However, more than half of the participants identified lack of funding and technical staff training as primary deterrents to the implementation and maintenance of R&R initiatives. This illustrates the difficulties that fee-for-service core facilities face when considering the costs associated with establishing new standardized procedures, methods, or technologies, or improving documentation, transparency, and quality control. When research and development costs are not supported, cores may have no choice but to use service rate increases to support research rigor. This may have the unfortunate outcome of driving investigators to seek alternative and cheaper service providers that may not invest in research best practices. These survey respondents report a lack of institutional and funding agency support and investment in research rigor, a lack of interest in research rigor among core service users, a lack of collaboration between core service providers and core service users, and a lack of standardization within and across technologies. These important issues may explain why 85% of survey respondents are not currently engaged in any efforts to address rigor and reproducibility at their home institutions despite their considerable concerns about research rigor and their clear interest in improving it.

Strategies for Improving R&R in Core Operation

Participants were asked to suggest solutions to mitigate or eliminate challenges and provide a clear path to improved R&R in cores. Only 27% of responders indicated that core SOPs and guidelines would be effective solutions to current R&R concerns. This relatively low percentage reflects the fact that these respondents have already actively adopted the use of routine SOPs within their cores. Some of the responders did emphasize the need for the development of universal guidelines and SOPs that would facilitate the consistent adoption across a technology or application and would incentivize investigators to comply with such published R&R guidelines.

A large consensus of participants (40%) proposed that funding mechanisms should be available to cores from either discretionary institutional funds or federal agencies to promote and support R&R initiatives. For instance, these funds could be used to offset the cost to the cores to develop improved quality control materials, optimize assays or laboratory information systems processes, or support multicore collaborations to improve consistency and quality. Similarly, a repeated suggestion recommended that funds be committed to protect or allocate time for core personnel to promote education and communication related to the work they do (and the expertise they can offer) to add value and reduce risk throughout research studies. One responder wrote "we have exponentially increased educational offerings to try to overcome our biggest issues (sample quality, proper controls, best practices, *etc.*), but whereas this works for researchers in the lab it doesn't always translate up to the PIs, and we see a general aversion to some of our recommendations due to cost restrictions."

Thirty-six percent of the respondents identified educational, technical, and scientific workshops, as well as mandatory project consultations with PIs and their laboratory staff, as critical to improving R&R in core-based sciences. Twenty-five percent of responders stated that it is essential to establish cores as full partners in the scientific research projects and to expand core input or authority for establishing requirements related to the quality assurance and quality control for the data they generate. Training programs for core users and core personnel that demonstrate best practices and the importance of scientific rigor on research outcomes were identified as practices that could help trainees understand the impact of research practices, thus facilitating compliance. It is clear that survey respondents believe that it is important to identify funding mechanisms to help core service providers become more visible as scientific experts, partners, and educators with the ability to directly influence research quality. These funding mechanisms could arise from research sponsor agencies that recognize the need to invest in research practices that support rigor and transparency. In addition, institutions must commit to good institutional practices by investing in research core activities. Respondents noted that institutions must also promote and develop opportunities for communication and outreach to facilitate development of productive relationships between these cores and their users. Some strategies may be as simple as featuring core personnel and expertise in internal seminar series, symposia, and scientific retreats. The current survey participant's call for improved institutional approaches that foster research rigor and reproducibility agrees with previously reported recommendations for institutional accountability.[2, 11]

About 25.6% of respondents noted that a radical cultural change at the highest institutional levels is necessary to support and foster research rigor and transparency. Research institutions, journals, and funding agencies must be willing to establish clear requirements as well as mandate and "provide incentives to support and monitor research rigor throughout the research life cycle." One respondent called for a "complete overhaul and reassessment of what constitutes quality research and start rewarding said qualities." A few remarked that there must be independent oversight or external audits to ensure adoption and compliance. One commented that "as long as the establishment controls the business from within, there won't be any major changes." These "cultural" observations related to research culture and incentives were frequently noted in previously published reviews of the research reproducibility issue.[1, 2, 9, 11]

Future Directions Supporting Scientific Research Core Services

The ABRF established the CCoRRe to develop resources to help scientific core facilities meet their specific research quality goals as well as the research rigor and reproducibility expectations articulated by the NIH. The NIH requirements were designed to "enhance the reproducibility of research findings through increased scientific rigor and transparency." In support of those goals, the CCoRRe committee plans to create a unique ABRF community page dedicated to R&R as a step toward identifying and addressing challenges the core communities face. This online community resource will include educational links, tools, and best-practice protocols or guidelines for the various scientific disciplines of the ABRF membership. It is our goal to identify and share opportunities for outreach and partnership with other professional societies and scientific journals implementing R&R in science. We plan to provide materials or examples from facilities and institutions that have developed effective strategies for meeting the expectations of the NIH related to research rigor and reproducibility. We aim to provide ABRF members with opportunities to learn how to implement rigor and reproducibility best practices into each core service as well as examples of how to demonstrate your adherence to those best practices within grant proposals and research reports.

CONCLUSIONS

Scientific shared resources support research laboratories to generate critical data across many disciplines. Core personnel maintain considerable expertise that is important for the quality of their work and for sharing with research scientists in their important role as research mentors. They ensure continuous improvement through professional and educational development and through their systematic approach to research methods.

Core science inherently supports transparency and scientific reproducibility, in part by protecting against cognitive bias in research design and statistical analysis.

Therefore, it is critical that core facilities lead the pursuit of research accountability and reliability. In this survey, the CCoRRe explored the perspective of research core personnel as it relates to research rigor and reproducibility in light of new expectations introduced by the NIH. This survey revealed barriers thought to restrict the ability of cores to establish, promote, and sustain research best practices. It also identified strategies and solutions for addressing these barriers. The survey illustrated that scientists and core service providers need additional support (training, time, resources, personnel, and guidelines) to implement and efficiently sustain best practices. In addition, they need the support of their institutions and users to ensure that there is a firm understanding of, and commitment to, the factors that support sound science and reproducible research outcomes. The goals of the NIH and other research stakeholders are more likely to be achieved when core facilities (already dedicated to maintaining and fostering rigor in methods development and data analysis) and research scientists work together to identify and minimize risk to research data, thereby improving research quality, rigor, and reproducibility. In light of current conversations related to the reproducibility of research, it is clear that the shared goals of research stakeholders, core facility personnel and users, and professional scientific societies such as the ABRF provide a timely opportunity to improve research outcomes across the complex research enterprise.

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